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Dove et al.

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(54) **BIOPROSTHETIC TISSUE WITH REDUCED CALCIFICATION**

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A61L 27/50 (2006.01)
A61F 2/24 (2006.01)

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(58) **Field of Classification Search**

None
See application file for complete search history.

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Primary Examiner — Robert A Wax

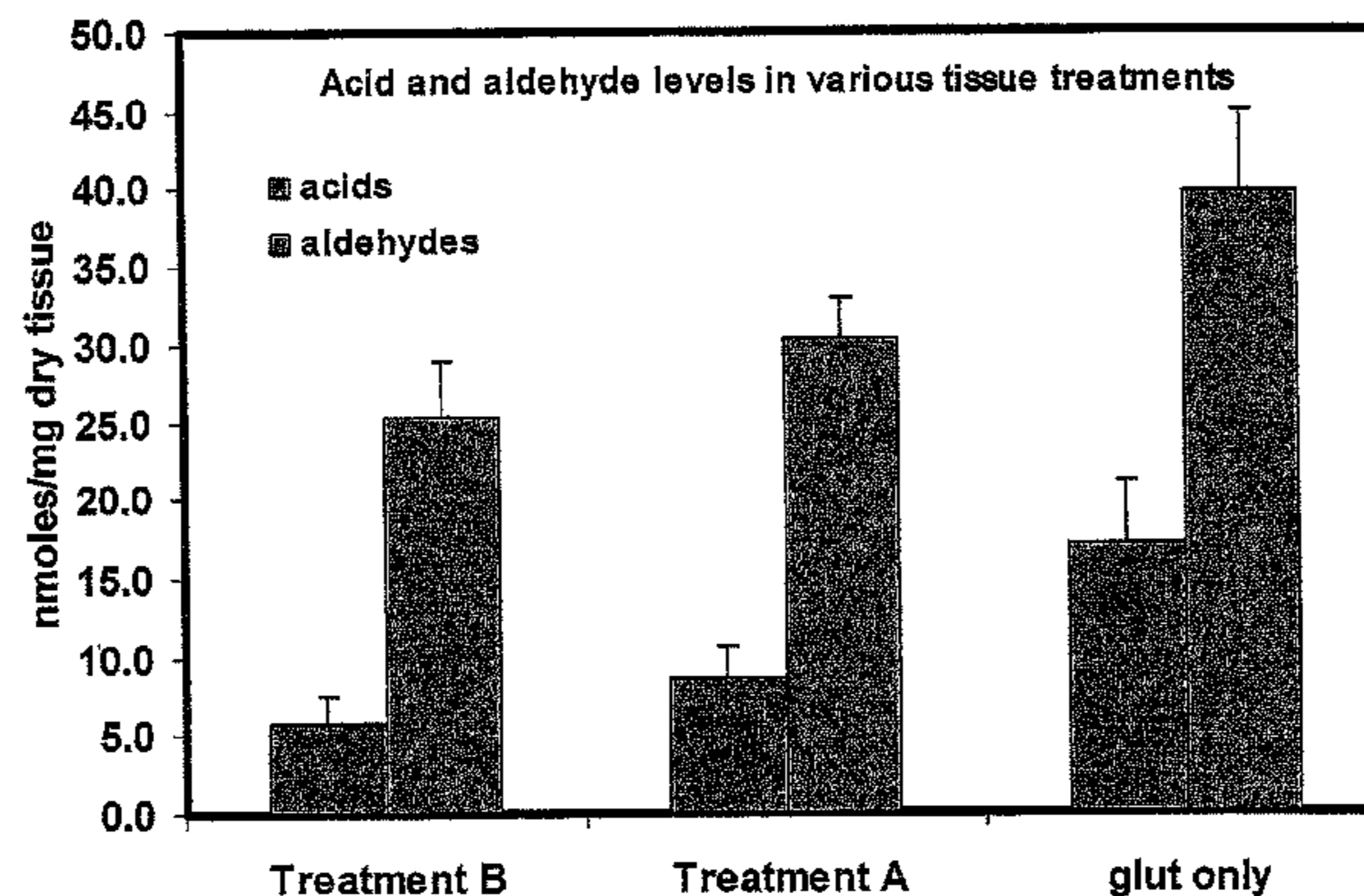
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(57) **ABSTRACT**

A treatment for bioprosthetic tissue used in implants or for assembled bioprosthetic heart valves to reduce in vivo calcification. The method includes applying a calcification mitigant such as a capping agent or an antioxidant to the tissue to specifically inhibit oxidation in tissue. Also, the method can be used to inhibit oxidation in dehydrated tissue. The capping agent suppresses the formation of binding sites in the tissue that are exposed or generated by the oxidation and otherwise would, upon implant, attract calcium, phosphate, immunogenic factors, or other precursors to calcification. In one method, tissue leaflets in assembled bioprosthetic heart valves are pretreated with an aldehyde capping agent prior to dehydration and sterilization.

10 Claims, 8 Drawing Sheets



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2400/02 (2013.01); *A61L 2430/20* (2013.01)

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Figure 1

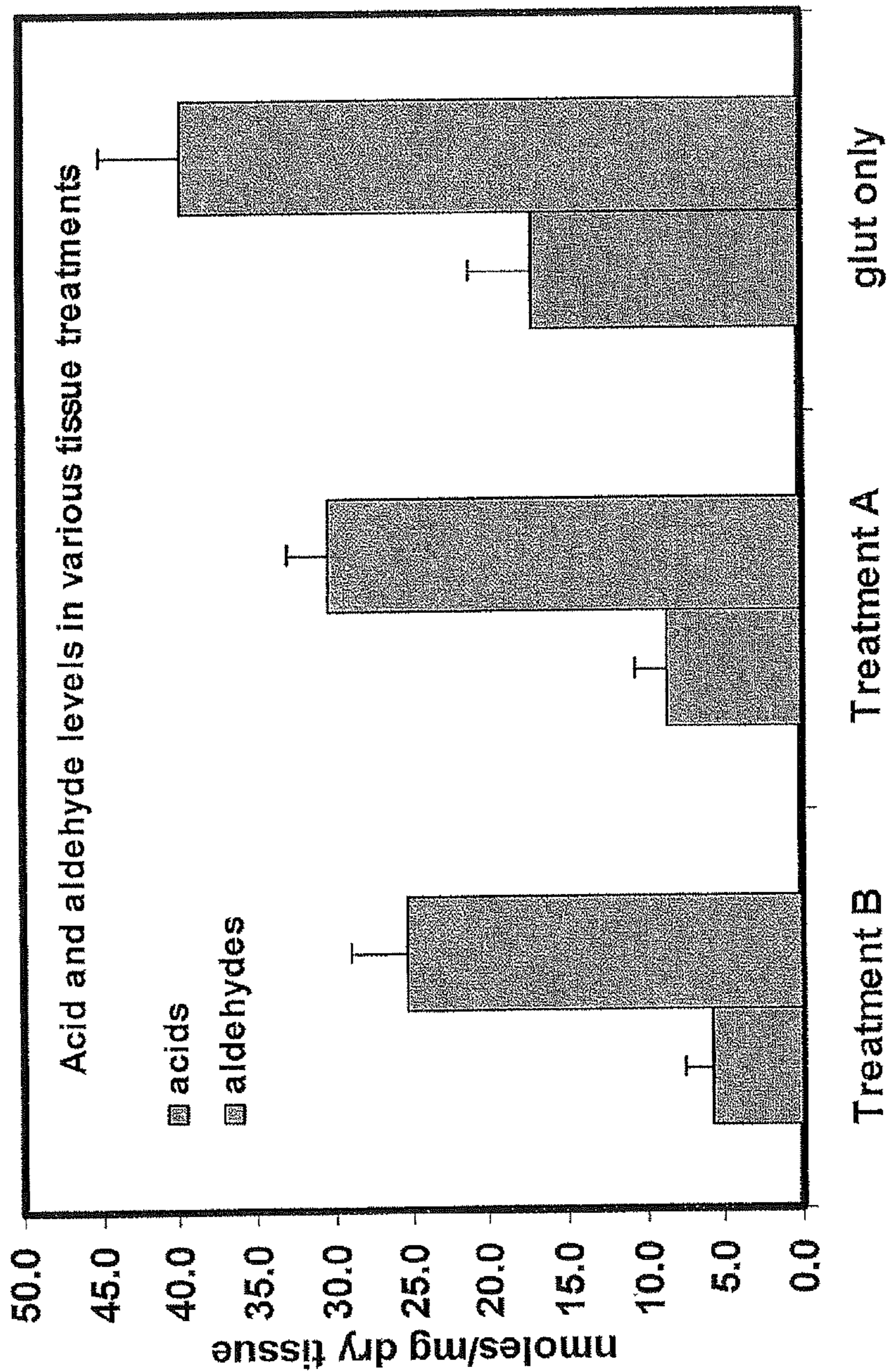


Figure 2

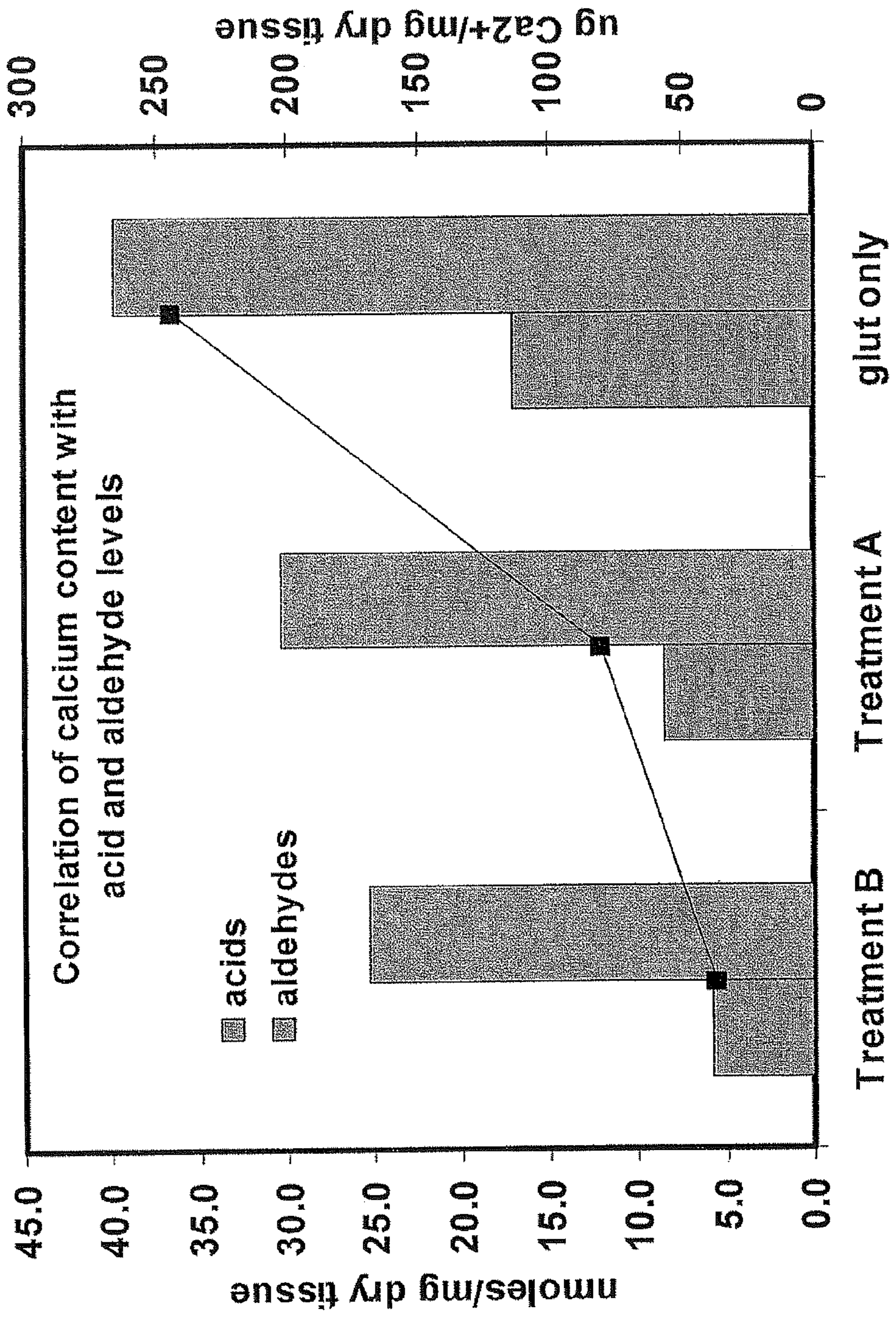


Figure 3

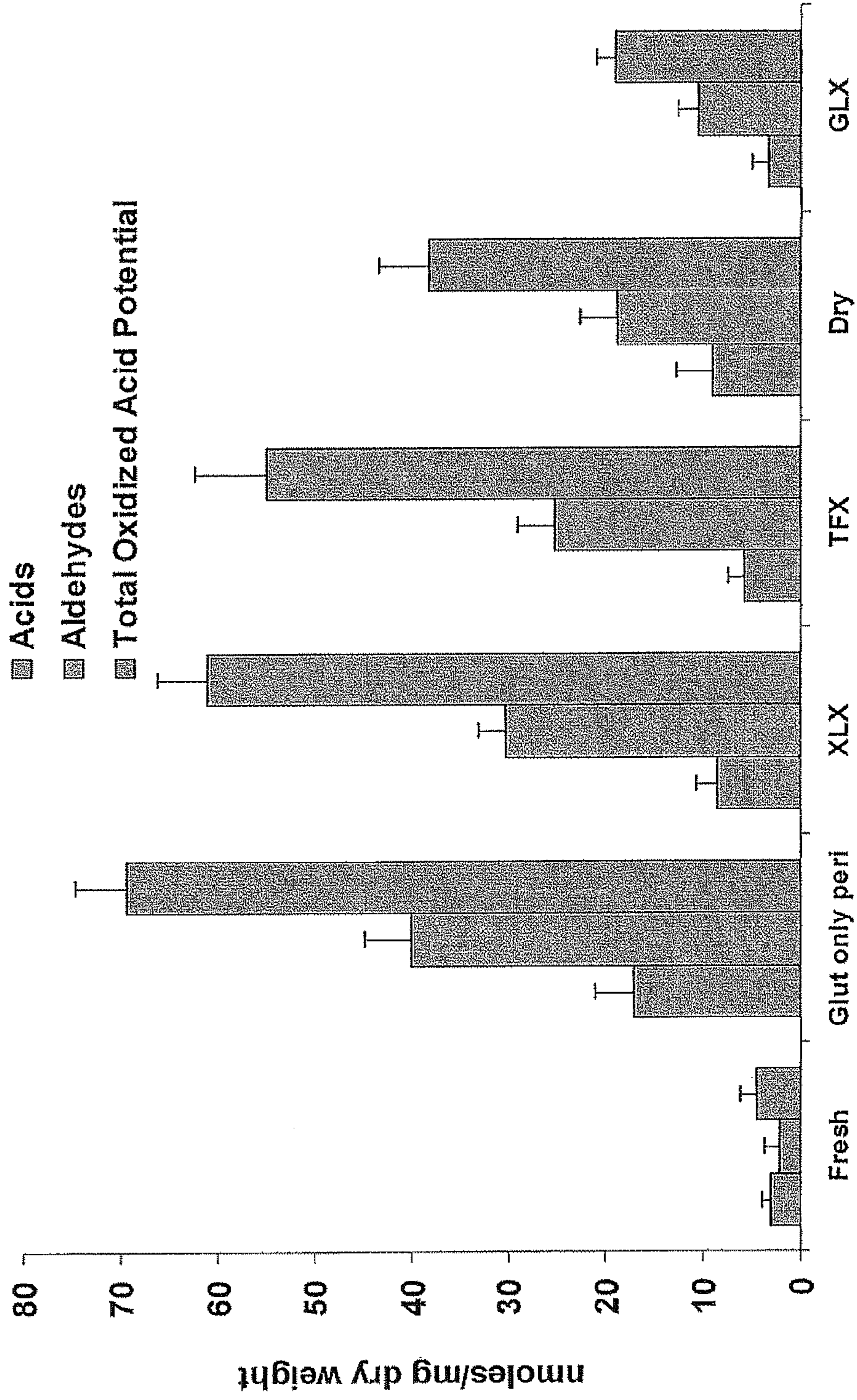
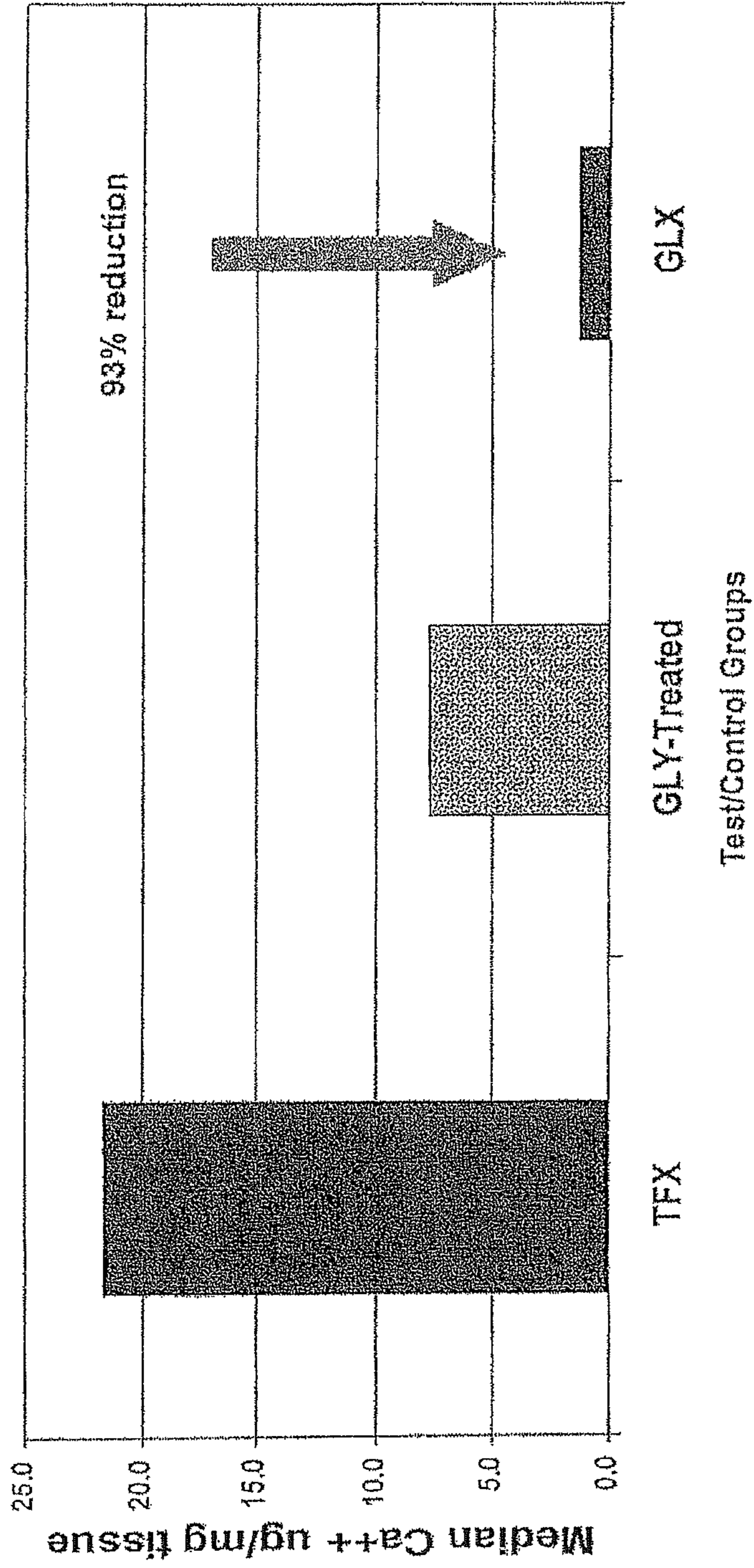


Figure 4

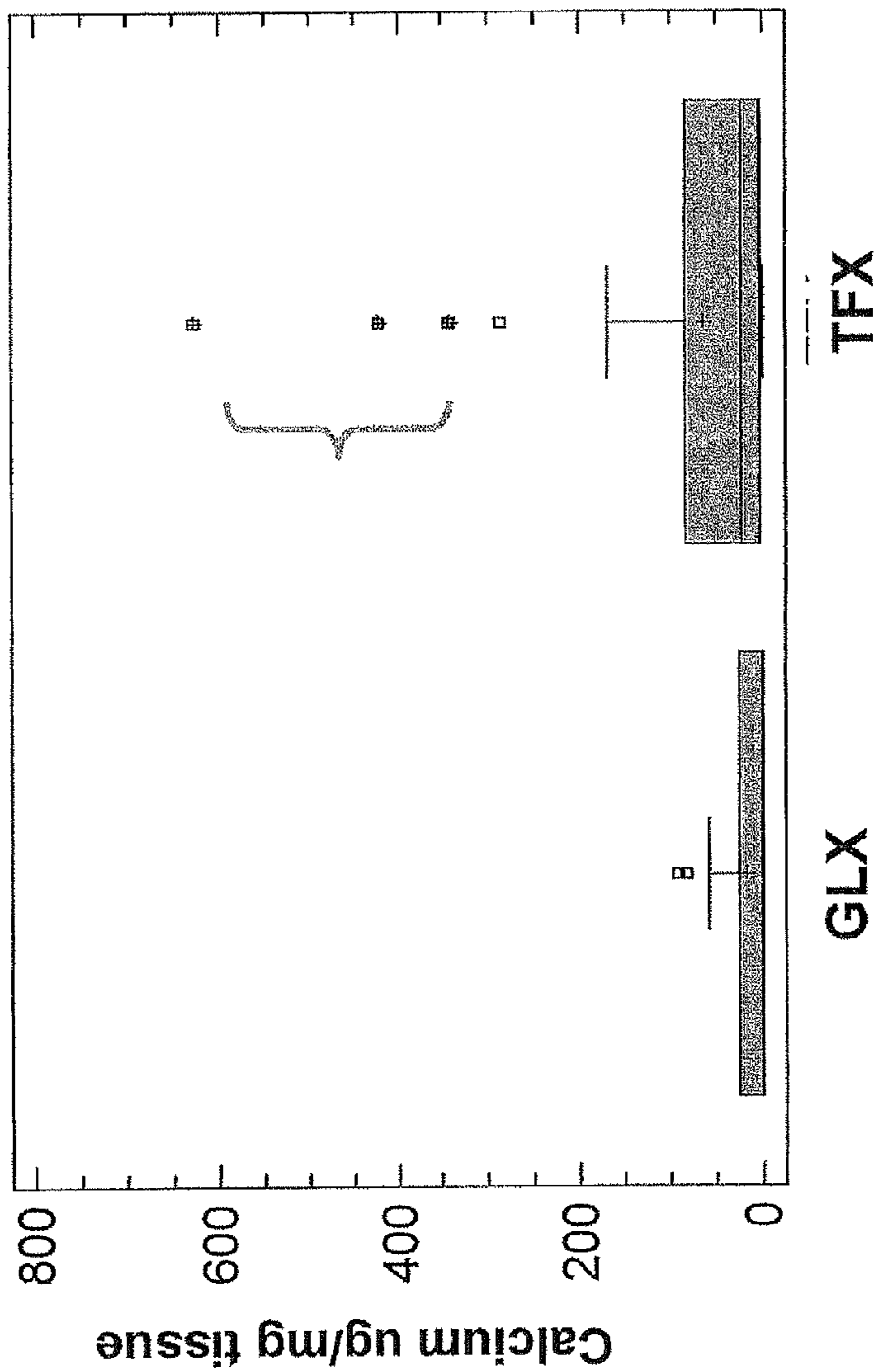
$n = 60$ | $p\text{-value} < .05$



Rabbit IM RD Study 1293

Figure 5

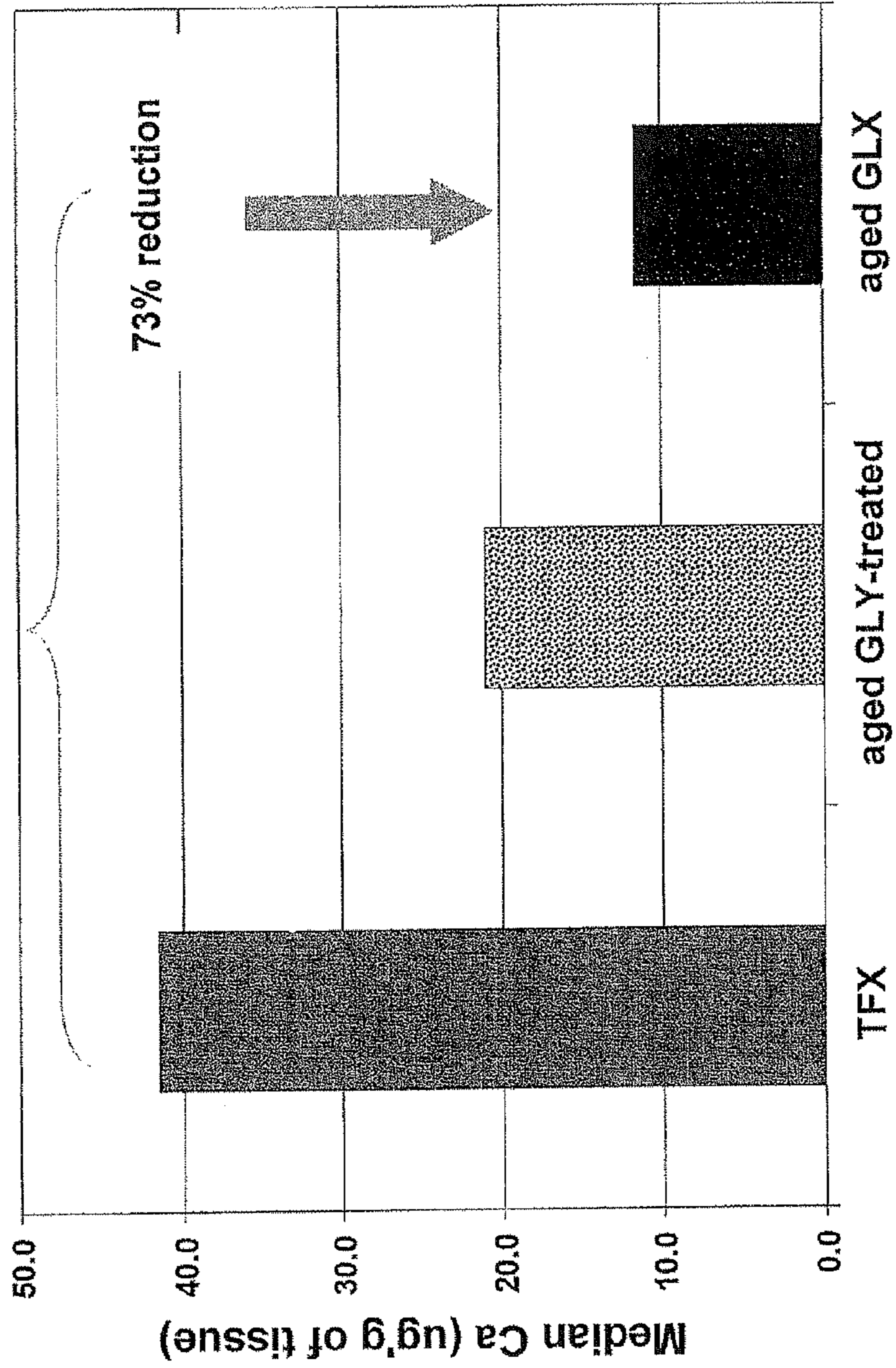
Rabbit IM Study



Rabbit IM RD Study 1293

Figure 6

$n = 60$ | $p\text{-value} < .05$

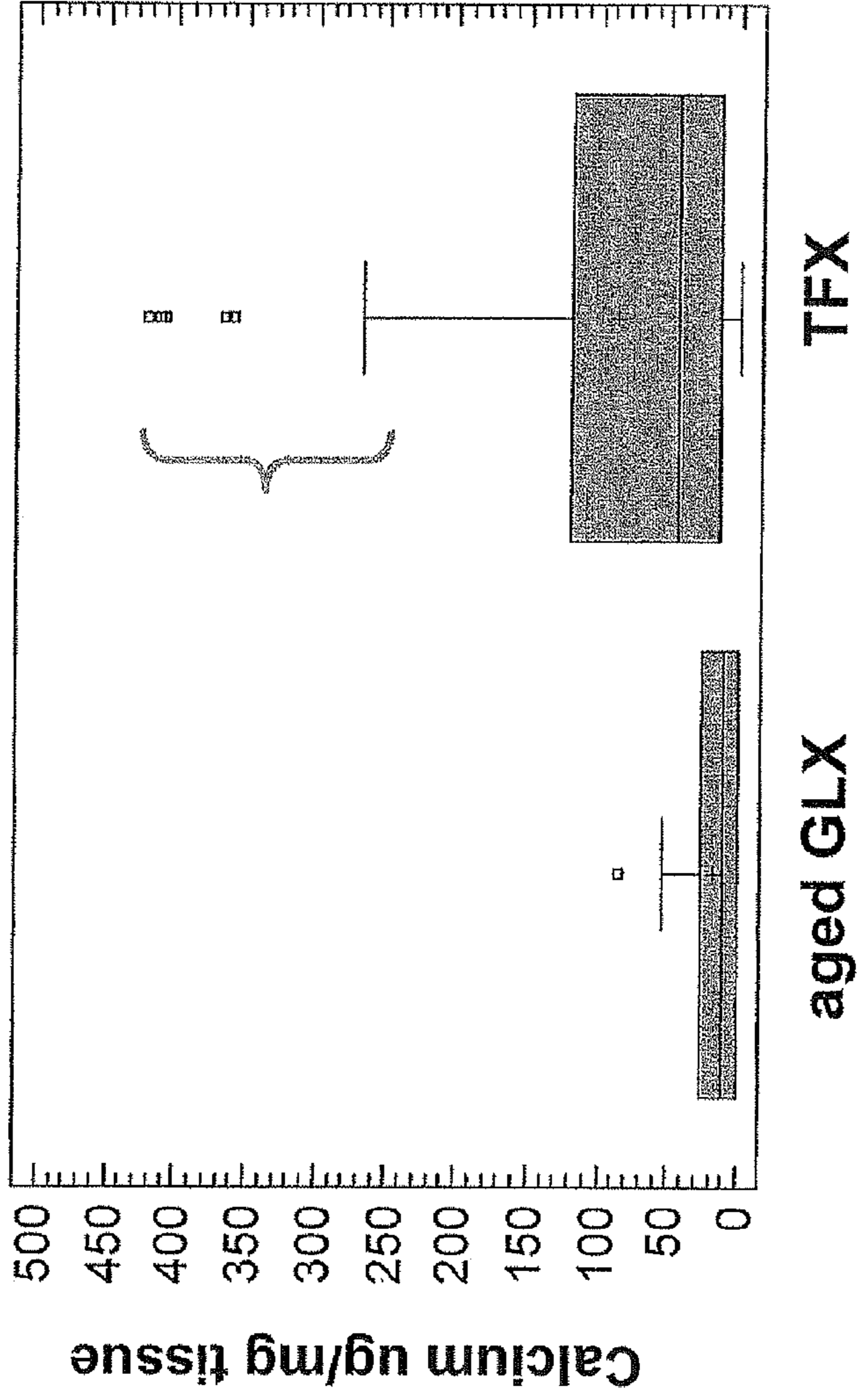


Rabbit IM RD Study 1313

*** Real-Time Aged Tissue

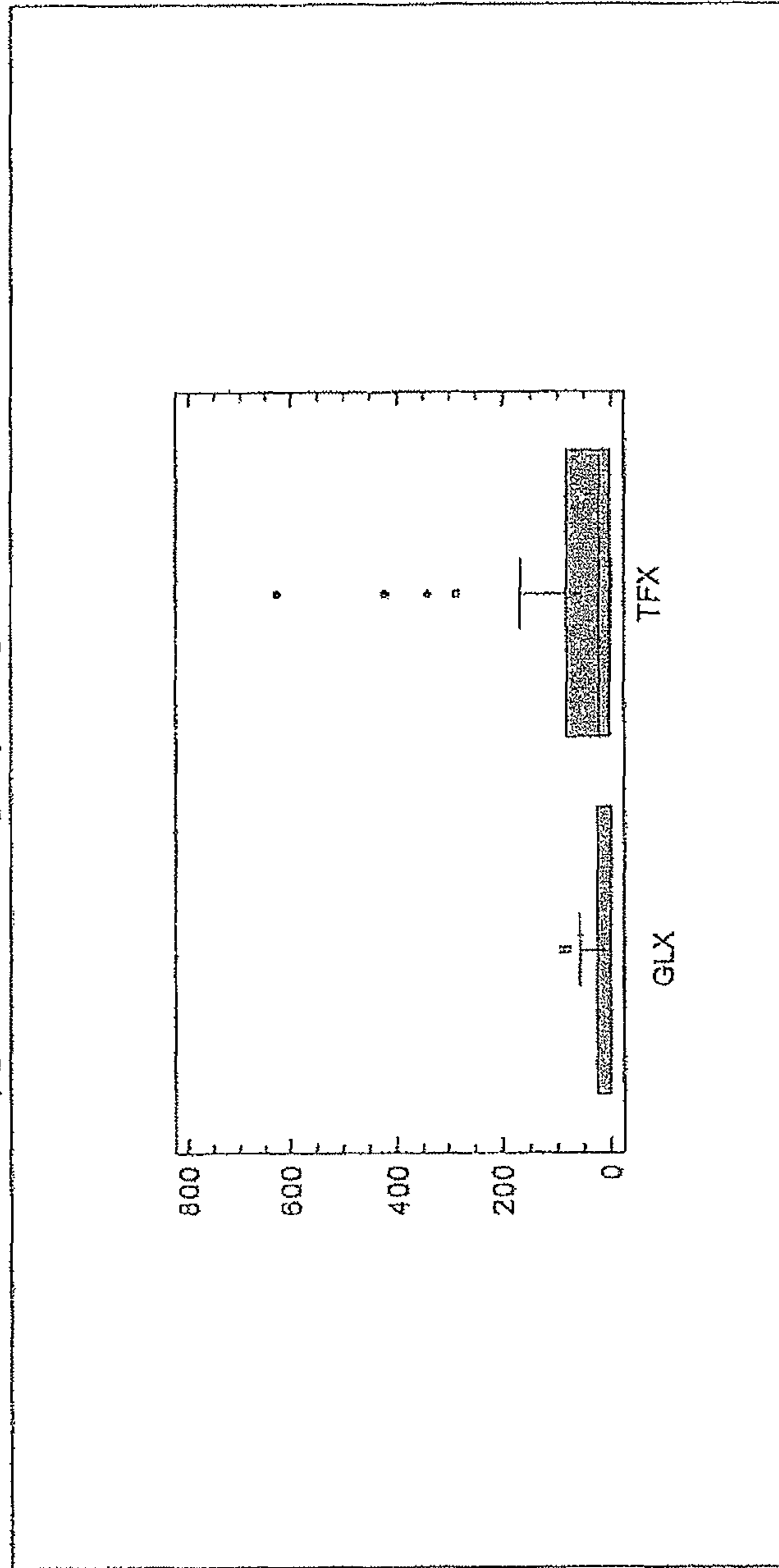
Figure 7

Rabbit IM Study



Rabbit IM RD Study 1313

Figure 8 – 35 Day Rabbit Intramuscular Study
μg calcium / mg dry weight tissue



BIOPROSTHETIC TISSUE WITH REDUCED CALCIFICATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 14/139,367, filed Dec. 23, 2013, now U.S. Pat. No. 9,029,418, which is a continuation of U.S. patent application Ser. No. 13/745,496, filed Jan. 18, 2013, now U.S. Pat. No. 8,748,490, which is a continuation of U.S. patent application Ser. No. 12/338,872 filed Dec. 18, 2008, now U.S. Pat. No. 8,357,387, which claims the benefit of U.S. Patent Application No. 61/016,263, filed Dec. 21, 2007, the entire disclosures of which are incorporated by reference herein.

FIELD OF THE INVENTION

The present invention relates generally to methods for treating bioprosthetic tissue, materials, and devices to reduce post-implantation calcification, and reducing post-implantation calcification, in particular for bioprosthetic tissue used in heart valves.

BACKGROUND OF THE INVENTION

Heart valve replacement may be indicated when there is a narrowing of the native heart valve, commonly referred to as stenosis, or when the native valve leaks or regurgitates, such as when the leaflets are calcified. In one therapeutic solution, the native valve may be excised and replaced with either a biologic or a mechanical valve. Certain medical conditions may require grafting or suturing a tissue patch to repair physiological abnormalities. These include, but are not limited to hernia repair, vascular wounds, congenital heart defect repair and reconstruction, and bladder wall repair.

Tissue-type or “bioprosthetic” valves have flexible tissue leaflets supported by a base structure that project into the flow stream and function much like those of a natural human heart valve by coapting against each other to ensure one-way blood flow. In tissue-type valves, a whole xenograft valve (e.g., porcine) or a plurality of xenograft leaflets (e.g., bovine or equine pericardium) typically provide fluid occluding surfaces. Synthetic tissue leaflets have also been proposed. One or more flexible leaflets mount within a peripheral support structure, for example as seen in the CARPENTIER-EDWARDS Porcine Heart Valve and PERIMOUNT Pericardial Heart Valve available from Edwards Lifesciences of Irvine, Calif.

Implantable biological tissues can be formed of human tissues preserved by freezing (i.e., cryopreservation) the homograft tissues, or of animal tissues preserved by chemically fixing (i.e., tanning) the xenograft tissues. The type of biological tissues used as bioprostheses include cardiac valves, blood vessels, skin, dura mater, pericardium, small intestinal submucosa (“SIS tissue”), ligaments and tendons. These biological tissues typically contain connective tissue proteins (i.e., collagen and elastin) that act as the supportive framework of the tissue. The pliability or rigidity of each biological tissue is largely determined by the relative amounts of collagen and elastin present within the tissue and/or by the physical structure and configuration of its connective tissue framework. Collagen is the most abundant connective tissue protein present in most tissues. Each collagen molecule is made up of three (3) polypeptide chains intertwined in a coiled helical configuration.

The techniques used for chemical fixation of biological tissues typically involve exposing the biological tissue to one or more chemical fixatives (i.e., tanning agents) which form cross-links between the polypeptide chains within a given collagen molecule (i.e., intramolecular cross-linkages), or between adjacent collagen molecules (i.e., intermolecular cross-linkages). Examples of chemical fixative agents that have been used to cross-link collagenous tissues include: formaldehyde, glutaraldehyde, dialdehyde starch, hexamethylene diisocyanate and certain polyepoxy compounds.

One problem associated with the implantation of many bioprosthetic materials is that the connective tissue proteins (i.e., collagen and elastin) within them can become calcified following implantation in the body. Such calcification can result in undesirable stiffening or degradation of the bioprostheses. This damage to the collagenous tissue leads to valve failure.

Of the various chemical fixatives available, glutaraldehyde (also referred to as simply “glut”) has been the most widely used since the discovery of its anti-immunological and anti-degenerative effects by Dr. Alain Carpentier in 1968. See Carpentier, A., *J. Thorac. Cardiovascular Surgery*, 58: 467-69 (1969). In addition, glutaraldehyde is one of the most common sterilization agents. Glutaraldehyde is therefore used as the preferred fixative and sterilant for many commercially available bioprosthetic products, such as in the bioprosthetic heart valves available from Edwards Lifesciences of Irvine, Calif. Glutaraldehyde creates potential calcium binding sites within the tissue that can lead to calcification in vivo, such as residual aldehydes, acids, Schiff bases, etc. These groups can contribute to calcification unless mitigated via capping. Mitigating such calcification is particularly important during storage, especially when the tissue is not being stored in aqueous solution.

Various techniques have been proposed for mitigating the in vivo calcification of glutaraldehyde-fixed bioprostheses or for otherwise improving the glutaraldehyde fixation process. Among these are methods described in U.S. Pat. No. 4,729,139 (Nashef); U.S. Pat. No. 4,885,005 (Nashef et al.); U.S. Pat. No. 4,648,881 (Carpentier et al.); U.S. Pat. No. 5,002,566 (Carpentier); EP 103947 (Pollock et al.), U.S. Pat. No. 5,476,516 (Seifter et al.), and U.S. Pat. No. 5,215,541 (Nashef et al.). The techniques in U.S. Pat. No. 5,862,806 (Cheung) include dehydration using an organic solution (i.e. ethanol, but no glycerol) of glutaraldehyde-treated tissues, prior to the application of a chemical reducing agent such as sodium cyanoborohydride or sodium borohydride in an organic solvent. This process involves only the addition of a reducing agent without any capping agents, such as proteins, amines or amino acids. The calcification mitigation techniques disclosed in U.S. Pat. No. 6,471,723 and U.S. Pat. No. 4,786,287 involve the addition of a variety of amines to detoxify the aldehyde groups in glutaraldehyde-fixed tissue. These chemicals are not permanently attached to the tissue (e.g., by addition of a reducing agent), and so diffuse out of the tissue over time, which dramatically lowers the calcium mitigation efficacy of these treatments. The techniques in U.S. Pat. No. 5,476,516 involve the addition of polyols (e.g., glycerol) and alcohols to bioprosthetic tissues as a calcification mitigation treatment alone, but do not address any oxidation mitigation (i.e., capping) strategies. U.S. Pat. No. 6,509,145 and U.S. Pat. No. 7,078,163 address oxidation of bioprosthetic tissue for the purpose of calcification mitigation. U.S. Pat. No. 6,630,001 and U.S. Pat. No. 6,277,555 discuss the use of glycerol preservation and lyophilization of tissue, but do not discuss chemical methods to prevent oxidation. U.S. Pat. No. 6,352,708 includes glycerol preservation of fresh, “non-

fixed" tissue, and treatments with glycerol and heparin, but does not include combinations of chemical treatments to prevent oxidation or reduce calcification with a glycerol drying step.

Recently a new technique of calcium mitigation by elevated-temperature fixation of the tissue in glutaraldehyde was described in U.S. Pat. No. 6,561,970 (Carpentier et al.) and in combination with relative tissue/fluid movement in U.S. Pat. No. 5,931,969 (Carpentier et al.). Another technique, involving adjusting the pH of a glutaraldehyde fixation solution, is disclosed in U.S. Pat. No. 6,878,168 (Carpentier et al.) The Edwards Lifesciences XenoLogiX™ Tissue Treatment eliminates up to 98% of phospholipids in an attempt to reduce calcium binding sites. In the Carpentier-Edwards ThermaFix™ Advanced Heart Valve Tissue Process, also from Edwards Lifesciences, both thermal and chemical treatments are used to remove unstable glutaraldehyde molecules and thus reduce calcium binding sites, resulting in a marked reduction in calcium uptake versus glutaraldehyde-only controls.

Bioprosthetic valves are generally stored in glutaraldehyde or formaldehyde solution, and must be rinsed prior to implantation. Glutaraldehyde is widely used as a storage solution due to its sterilant properties but is known to contribute to calcification. Strategies to minimize glutaraldehyde content in the final product have been demonstrated to mitigate in vivo calcification. Studies have shown that storage solutions without glutaraldehyde reduce in vivo calcification compared to those with glutaraldehyde. (Mirzaie, et al. *Ann Thorac Cardiovasc Surg* 2007 13:102).

One such strategy to avoid glutaraldehyde as a storage solution is to dehydrate the bioprosthetic tissue in a glycerol/ethanol mixture, sterilize with ethylene oxide, and package the final product "dry". This process circumvents the potential toxicity and calcification effects of glutaraldehyde as a sterilant and storage solution. There have been several methods proposed to use glycerine, alcohols, and combinations thereof as post-glut processing methods so that the resulting tissue is in a "dry" state rather than a wet state with excess glut. These approaches avoid the use of aqueous liquid aldehyde, or liquid sterilant as storage solutions for tissue and devices. Glycerol-based methods can be used for such storage as described in the following examples. The storage of heart valve tissue in glycerol was described by Parker et al. (*Thorax* 1978 33:638), but does not include any calcification mitigation techniques and does not describe any advantages. Also, U.S. Pat. No. 6,534,004 (Chen et al.) describes the storage of bioprosthetic tissue in polyhydric alcohols such as glycerol. However, neither of these addresses mitigating potential oxidation of the tissue.

In processes where the tissue is dehydrated in an ethanol/glycerol solution, the tissue may be sterilized by ethylene oxide, gamma irradiation, or electron beam irradiation. Ethylene oxide sterilization requires exposing the tissue to increased temperatures and water vapor which will generate oxidative damage in the tissue (Olde Damink, L H. et al. *J Biomed Mater Res* 1995 29:149). Gamma irradiation is known to generate significant reactive oxygen species in collagenous substrates which causes backbone scission and breakage of collagen fibrils (Ohan, M P et al. *J Biomed Mater Res A* 2003 67:1188). This damage will lead to decreased mechanical and biochemical functionality in the tissue. Electron beam irradiation will also cleave the collagen backbone and lead to deterioration of the tissue structure and reactivity (Grant, R A et al. *J Cell Sci* 1970 7:387). Damage from oxidation during sterilization and/or storage will contribute to valve deterioration and structural failure. U.S. Pat. No. 6,605,

667 discusses the addition of various antioxidant stabilizers to polymerizable adhesives, but does not address damage mitigation to bioprosthetic tissue by ionizing radiation or oxidation during storage.

Although these glycerol-based methods are useful as alternatives to storage in aqueous, liquid-type solutions, they do not address the fact that the post-process functional groups (i.e. aldehydes) can oxidize over time and thus increase the potential for calcification. The present invention describes a capping method such that oxidation and other changes are dramatically reduced with storage time. The prior art does not address the changes within dehydrated bioprosthetic tissue during storage that occur as a result of in vitro oxidation by air or in vivo oxidation. The high aldehyde content in glutaraldehyde-fixed tissue is highly susceptible to oxidation, which results in calcification and tissue failure. Thus, the present invention teaches an improved tissue treatment method for implantable tissue devices.

The present invention addresses certain detrimental changes within dehydrated tissue that can occur as a result of oxidation either from sterilization, atmospheric exposure during storage and handling, or from in vivo oxidation. Storage of bioprosthetic tissue in glutaraldehyde provides some antioxidant effect and helps to prevent oxidation of the aldehyde functions in the tissue that are likely to contribute to increased calcification. In processes where the tissue is dehydrated and stored in air, the tissue is not protected from oxidation and will lead to biochemical damage from reactive oxygen species. The resulting oxidative biomarkers, such as carboxylic acids, are likely to promote calcium binding and proceed to failure of the bioprosthesis due to calcification. The permanent capping of the aldehyde groups in the tissue (reductive amination) will prevent significant oxidation of the tissue and lead to longer service lifetimes of the material. The present invention involves the chemical capping of aldehydes (and other species) or otherwise neutralizing of the tissue to prevent oxidation in dehydrated tissue.

The invention also describes the addition of chemicals (e.g. antioxidants) to the dehydration solution (ethanol/glycerol) to prevent oxidation of the tissue during sterilization (ethylene oxide, gamma irradiation, electron beam irradiation, etc.) and storage. Dehydrated bioprosthetic tissue is particularly susceptible to oxidation during sterilization and storage. The prior art does not discuss the chemical prevention of this damage for this type of bioprosthetic material.

SUMMARY OF THE INVENTION

One object of the invention is to provide a method of mitigating calcification in bioprosthetic implant tissue, comprising: a) treating bioprosthetic implant tissue with a capping agent that reacts with functional groups on said tissue, and b) dehydrating the capped tissue with a non-aqueous solution.

Another object is to provide calcification-resistant tissue, comprising: a) bioprosthetic implant tissue that has been treated with a capping agent which reacts with functional groups on said tissue, and b) dehydrated with a non-aqueous solution.

A further understanding of the nature and advantages of the present invention are set forth in the following description and claims, particularly when considered in conjunction with the accompanying drawings in which like parts bear like reference numerals.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a graph showing the aldehyde and acid content in bovine pericardial tissue after several different chemical treatments;

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FIG. 2 is a graph correlating the calcium content of in vivo tissue with the corresponding acid and aldehyde content for tissue treated three different ways;

FIG. 3 is a graph illustrating the acid and aldehyde content of various tissue treatments;

FIG. 4 is a chart showing the decrease in calcification by capping, reduction and drying (GLX process);

FIG. 5 is a chart that indicates the reduction in calcification variability by capping, reduction and drying (GLX process);

FIG. 6 is a chart showing the decrease in calcification by capping, reduction and drying (GLX process) after 80 days of real time shelf life;

FIG. 7 is a box and whisker plot of 35 Day Rabbit Intramuscular Study.

FIG. 8 is a box and whisker plot of 35 Day Rabbit Intramuscular Study, Short Term Shelf Life and Calcification

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention provides an improved bioprosthetic tissue treatment process that greatly reduces the potential for calcification after implantation by blocking free aldehyde groups prior to a dehydration step and/or the addition of chemical agents to prevent oxidative damage during sterilization. "Bioprosthetic tissue" includes, without limitation, bovine pericardium and porcine tissue which are commonly used in bioprosthetic heart valves, and blood vessels, skin, dura mater, pericardium, small intestinal submucosa ("SIS tissue"), tissue heart valves, ligaments and tendons. "Implants" in the present application refers not only to heart valves, including transcatheter heart valves, but also to vascular prostheses and grafts, tissue grafts, bone grafts, and orbital implant wraps, among others.

A "bioprosthetic heart valve" refers to a fully assembled prosthetic valve made at least partly from bioprosthetic tissue. Some whole porcine valves are used in so-called "stentless" bioprosthetic valves in which there is very little if any synthetic material added for support or anchoring purposes. A "stented" bioprosthetic valve typically has some kind of synthetic (e.g., polymer or metallic) support for the leaflets, which may be the leaflets of a whole porcine xenograft or separate bovine pericardial leaflets. Heart valves contemplated herein include surgical heart valves, transapical heart valves, transfemoral heart valves and other types of heart valves.

Prior art tissue treatments address crosslinking, microbes, and other aspects of the tissue in a "static" setting, and typically involve immersion of the tissue in glutaraldehyde, Tween (polyoxyethylene 20 sorbitan monooleate), ethanol, formaldehyde, and other agents to mitigate post-implant calcification. Some prior art processes include the addition of various chemicals to reduce the toxicity of the crosslinked tissue or mitigate calcification via the use of metal ions (i.e., Al^{3+} or Fe^{3+} —see U.S. Pat. No. 5,746,775, Levy) or bulk blocking agents (i.e., 2-amino oleic acid—see U.S. 4,976,733, Giradot). But each of these methods is only applied to initially processed tissue, not to dehydrated tissue or tissue devices to prevent oxidative damage. The prior art processes are limited to the addition of chemical or biological agents to crosslinked tissue that are temporarily attached to the tissue, or they are limited to reduction or oxidation of the tissue alone without any addition of "capping agents" (e.g., U.S. Pat. No. 5,862,806, Cheung).

Unlike the various prior art tissue processes, where the goal is to fix (i.e. crosslink, etc.) the tissue, this invention describes an additional process whereby acids and other potential bind-

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ing sites formed from the prior art fixation processes are "capped." It also involves "capping" the binding sites and potential binding sites that are generated from oxidation of fixed tissue. Tissue treatment with glutaraldehyde, Tween (polyoxyethylene 20 sorbitan monooleate), ethanol, formaldehyde, and other agents can provide useful fixation of the tissue. However, it will also generate binding sites capable of interacting with or attracting calcium, phosphate, immunogenic factors, or other precursors to calcification. For example, there are many negatively charged carboxylic acid groups formed after glutaraldehyde fixation of the tissue, and these groups are capable of attracting calcium ions (due to their negative charge and electrostatic interactions with positively charged ions) leading to calcification of the tissue or adverse cellular interactions. Carboxylic acid groups like those in glutamic acid or gamma carboxy glutamic acid are known to bind calcium atoms (Hauschka et al. *PNAS* 1975 72:3925). Calcium binding proteins such as bone sialoprotein contain carboxylic acid-rich domains designed to attract and bind calcium, leading to hydroxyapatite formation (calcification). The overall level and location of acid groups in these proteins determines the ability of the protein to efficiently bind calcium and form hydroxyapatite. The term "acid potential" of the tissue refers to the level of these chemical functional groups within the fixed tissue which may eventually form acid groups or "binding sites" by oxidation, dehydration, hydration, or similar processes.

The inventors have discovered that such binding, causes significant post-implant damage in bioprosthetic materials, especially tissues used for heart valve leaflets. For example, the oxidative damage that occurs during storage and handling of dehydrated or "dry" tissue can create carboxylic acid groups that will bind calcium and lead to tissue failure. This progressive leaflet damage process can create new binding sites or potential binding sites that are precursors to calcification and immunogenic related pathways. The present invention describes a method to cap these newly formed binding sites prior to implantation of the tissue for tissue-based bioprosthetic into the body. The inventors have also discovered that bioprosthetic tissue exposed to oxidation from the atmosphere when not submersed in a glutaraldehyde solution or during sterilization is likely to contain more acid groups that contribute to calcification and inflammation. In dry storage, the dehydrated tissue is sterilized and stored "dry" without the protective effect of the glutaraldehyde solution. The ease of handling and storage of this new product is greatly facilitated due to the absence of the glutaraldehyde storage solution. This technology can be improved by treating such bioprosthetic tissue with a capping agent and/or adding a chemical protectant during the dehydration phase.

One chemical target within the invention is the permanent "capping" of the acid groups which dramatically reduces their ability to attract calcium, phosphate, immunogenic factors, or other groups. The term "capping" refers to the blocking, removal, or alteration of a functional group that would have an adverse effect on the bioprosthesis properties. For example, the addition of 1-ethyl-3-[3-dimethylaminopropyl] carbodiimide hydrochloride (EDC), N-hydroxysulfosuccinimide (sulfo-NHS), and ethanolamine will effectively cap the acid groups with a non-reactive alcohol group.

In addition to acid binding sites, tissues treated with glutaraldehyde or other aldehyde-containing agents also yield tissue with many free aldehyde groups that cause increased toxicity, higher calcification, and involvement in immunogenic responses. These aldehyde groups can easily oxidize into carboxylic acid groups via air oxidation, in vivo blood oxidation, macrophage oxidation, and other similar oxidation

pathways. Thus, an additional target of the invention includes the permanent capping of aldehyde groups, which are potential binding sites, in a way that would prevent or mitigate their ability to transform into acids or other groups and thus further mitigate the potential for calcification in the body (in vivo). In addition to acids and aldehydes there are other possible binding sites such as immunogenic and antigenic factors, capping which is included within the scope of this invention.

The present capping process includes chemical reduction of the tissue, which, when applied to the tissue in the presence of a capping agent, will permanently connect the capping agent to the target group. For example, the addition of ethanolamine to the tissue will cap the aldehyde groups, while the reducing agent (e.g., sodium borohydride) reduces any Schiff base created by reaction of the aldehyde with the amine group of ethanolamine. Thus an aldehyde is ultimately replaced by a hydroxyl group, which may be beneficial for tissue hydration, flexibility, and cell interactions. Of course, other capping agents can be used instead of ethanolamine and other reducing agents other than sodium borohydride and are known by those skilled in the art and which are included in the scope of this patent. Another preferred strategy is to oxidize the tissue aldehydes to acids, and then cap the acid groups. This may involve the addition of 1-ethyl-3-[3-dimethylaminopropyl] carbodiimide hydrochloride (EDC), N-hydroxysulfosuccinimide (sulfo-NHS), and ethanolamine. These new "capped" groups will reduce the attraction of calcium, phosphate, immunogenic factors, or other similar agents.

In one specific embodiment, the invention provides a method of treating bioprosthetic implant tissue to reduce in vivo calcification of comprising at least partially cross-linking bioprosthetic implant tissue, then treating the cross-linked tissue with an aldehyde (or acid) capping solution to mitigate calcification, and dehydrating the tissue in an ethanol/glycerol solution. The glycerol solution may include an antioxidant treatment and may contain a water-soluble wax. The tissue is then allowed to dry and then subjected to final sterilization (e.g., ethylene oxide, gamma irradiation, or electron beam irradiation). The following steps describe an implementation of this process in the manufacture of prosthetic heart valves.

Aldehyde Capping. After the valve leak and flow inspection, the valves are briefly rinsed in 20% ethane to remove any excess glutaraldehyde adhering to the tissue. This is thought to enhance the capping process by ensuring that the capping solution can attach to aldehydes on the tissue rather than free glutaraldehyde in solution. The valves are then exposed to a capping solution of ethanolamine and sodium borohydride, at room temperature under agitation for 4 hours. Valves are removed from the capping solution, and rinsed for a few minutes at room temperature with the same solution used in the final bioburden reduction process to remove excess capping solution.

Glycerol Treatment. After the valves have been processed through a standard final bioburden reduction step, they undergo the glycerol treatment in a solution of 75 wt % glycerol and 25 wt % ethanol. Valves are soaked in this solution for one hour at room temperature. During this time, most of the water molecules present in the pericardial tissue are replaced with glycerol. Valves are removed from the solution and placed in a clean hood to allow any excess solution to evaporate or drip off the valves.

EO Sterilization. The dehydrated valves are then ready for packaging. They are packaged in double sterile barrier packaging consisting of a rigid tray (PETG) with a Tyvek lid. The package is sealed in a cleanroom, and sterilized in 100% ethylene oxide.

The calcification mitigant preferably contains a capping agent selected from:

- an amine,
- an amino acid,
- an amino sulfonate,
- a hydrophilic multifunctional polymer,
- a hydrophobic multifunctional polymer,
- α -dicarbonyl,
- a hydrazides,
- a N,N-disuccinimidyl carbonate,
- a carbodiimide,
- 2-chloro-1-methylpyridinium iodide (CMPI),
- an antibiotic,
- a cell recruiting agent,
- a hemocompatibility agent,
- an antiinflammatory agent,
- an antiproliferative agent,
- an immunogenic suppressing agent,
- a reducing agent, and
- a mono-, di- or polyepoxy alkane.

The chemical anti-oxidant is desirably selected from:

- a water soluble antioxidant such as ascorbic acid,
- a fat soluble antioxidant such as tocopherols,
- a carbohydrate such as fructose,
- sucrose,
- or mannitol
- a hindered phenol such as butylated hydroxytoluene (BHT),
- a hindered amine light stabilizer (HALS) such as p-phenylamine diamine,
- trimethyl dihydrodquinoline,
- or alkylated diphenyl amines
- a phosphite/phosphonite such as triphenyl phosphine,
- and a thioester such as a thiocinnamate

The calcification mitigant (capping agent) and/or the chemical oxidation protectant is desirably delivered in one or a combination of the following selected solutions:

- an aqueous solution such as an aqueous buffered solution, water, short chain alcohols, glycerol, or plasticizers,
- an organic solvent, and
- an organic buffered solution.

The tissue is preferably fully cross-linked prior to the capping process. In one embodiment, the tissue comprises precut heart valve leaflets mounted and treated in a suitable apparatus. Alternatively, the tissue may be bulk sheets of tissue treated in a suitable apparatus.

Examples of capping agents, provided in species and sub-species, are:

- amines,
- alkyl amines,
- amino alcohols,
- ethanolamine,
- amino acids,
- lysine,
- hydroxylysine,
- amino sulfonates,
- taurine,
- amino sulfates,
- dextran sulfate,
- chondroitin sulfate,
- hydrophilic multifunctional polymer,
- polyvinyl alcohol,

polyethyleneimine,
 hydrophobic multifunctional polymer,
 α -dicarbonyls
 methylglyoxal
 3-deoxyglucosone
 glyoxal
 hydrazides
 adipic hydrazide
 N,N-disuccinimidyl carbonate
 carbodiimides
 1-ethyl-3-[3-dimethylaminopropyl]carbodiimide hydrochloride (EDC)
 N-cyclohexyl-N'-(2-morpholinoethyl)carbodiimide (CMC)
 1,3-dicyclohexyl carbodiimide (DCC)
 2-chloro-1-methylpyridinium iodide (CMPI)
 an antibiotic,
 a cell recruiting agent,
 a hemocompatibility agent,
 heparin,
 an anti-inflammatory agent,
 an antiproliferative agent,
 an immunogenic suppressing agent,
 a reducing agent,
 sodium cyanoborohydride,
 sodium borohydride,
 sodium bisulfite+acetylacetone,
 formic acid+formaldehyde, and
 mono-, di- or polyepoxy alkanes.

The effect of preferred capping agents is to not only block functional groups that will attract calcium, phosphate, immunogenic factors, or other similar agents, but to replace those groups with a superior biological functionality. The term "biological functionality" is defined as the effect of tissue components on the local biology of the implanted material. Improved biological functionality of a tissue treatment may include reduction in overall charge of the tissue, better hemocompatibility, increased tissue hydration, better cell interactions, better flexibility, etc. For example, capping aldehyde functions with ethanolamine blocks the aldehyde group from oxidizing into an acid and replaces it with a hydroxyl group, which may be beneficial for tissue hydration, flexibility, and cell interactions. The desired biological functionality of the capped tissue will determine the type of capping compounds employed.

The capping strategy is also designed to block the biological functionality of components of the tissue that may contribute to adverse cellular reactions. Some of these targets include, but are not limited to α -gal, MHC-1 associated proteins, HLA antigens and the like. The invention addresses the capping or blocking of proteins, carbohydrates, lipids, and other components of the tissue that may contribute to cellular reactions. For example, the α -gal carbohydrate may be blocked by treatment with 2-chloro-1-methylpyridinium iodide (CMPI) and other agents that neutralize the hydroxyl groups which are known by those skilled in the art. Another example includes MHC-1 associated proteins that may be capped or effectively neutralized by treatment with 1-ethyl-3-[3-dimethylaminopropyl]carbodiimide hydrochloride (EDC) and ethanolamine. Also included in the invention's capping process is the targeting of proteins, carbohydrates or lipids associated with cell and vessel remnants. For example, fibronectin may be capped or blocked by the addition of methylglyoxal to the tissue. This dicarbonyl is known to bind critical arginine functions within proteins and impairs the biological functionality of these proteins.

Another aspect of the invention includes the activation of capping technology upon sterilization. For example, the treatment of tissue with specific capping agents (e.g. glucose and ethanolamine or taurine) prior to gamma irradiation sterilization would produce activation of the capping agents upon irradiation. The capping agents added to the tissue would effectively cap targets within the tissue immediately, but sterilization (i.e. ethylene oxide, electron beam irradiation, or gamma irradiation) would generate new binding sites that would then be capped by the residual capping agents within the tissue. Gamma irradiation of collagen is known to cleave peptide bonds within the backbone and produce new functional groups that may have adverse effects on the tissue. These new functional groups are included in the targets or binding sites described herein and may be capped or blocked by the capping agents listed herein.

Immunogenic factors are defined as anything causing or involved in stimulating an immunogenic response. These include any chemical or biological agent capable of inducing an immune type response. For example, vessel and cell membrane components left in the tissue may cause some type of immunogenic or antigenic response from the body's natural immune system. The invention includes capping agents capable of masking, replacing, or blocking these immunogenic elements in the tissue either statically or dynamically. For example, a whole valve could be fixed, then capped with a non-immunogenic or more hemocompatible capping agent such as heparin prior to dehydration and sterilization. This is different from prior art processes that add heparin to fixed tissue without any dehydration of the valve or any consideration of the post-process oxidation conditions. The invention process can be supplemented with a decellularization process to reduce immunologic or antigenic binding sites and potential binding sites and is also within the scope of this invention.

To better understand the principles underlying the treatment techniques of the present invention, a number of graphs in (see the Figures) are presented based on actual testing. As mentioned above, the invention generally comprises treating tissue so that calcium or phosphate binding sites, or other such sites which could trigger calcification, are capped. The correlation between acid binding sites and tissue calcification can be seen in (FIG. 2 see also Hauschka et al. *PNAS* 1975 72:3925) and it appears that acid templating directs mineralization in a variety of species. Thus, the amount of free acids and/or aldehydes in the tissue at the time of implantation correlates with the number of such binding sites and, therefore, increases the potential for calcification. The amount of free acids and aldehydes present in tissue can be measured by known methods, for example, a standard spectrophotometric assay.

FIG. 1 is a graph showing both the free aldehyde and free acid content in bovine pericardial tissue as measured by the aforementioned technique. It should be understood that all of the tests referred to herein involve glutaraldehyde-fixed bovine pericardial tissue. The tissues studied have all been chemically treated, one with glutaraldehyde only, and two others with tissue treatments that have been used by Edwards Lifesciences to prepare commercial bioprosthetic tissue for implant. However, other cross-linking and tissue processing methods can be used and are within the scope of this invention.

The aldehyde and acid content of the tissues is measured subsequent to the chemical treatments, and without any damage or stress imparted to the tissue. On the right side of the graph of FIG. 1, the tissue samples have been treated in glutaraldehyde only, in particular in a solution of 0.625% glutaraldehyde for a period of 14 days. A total of 10 samples

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were treated and subsequently tested. The measurements showed an average level of about 40 nanomoles of aldehydes and about 17 nanomoles of acids per milligram of dry weight of the tissue.

The middle of the graph of FIG. 1 shows the results from testing a total of 10 tissue samples subjected to Treatment A, which is commercially known as the XenoLogiX™ tissue treatment process from Edwards Lifesciences of Irvine, Calif. Treatment A involves first fixing with glutaraldehyde then treating twice with a sterilant including a cross-linking agent such as formaldehyde, a surfactant such as Tween-80 (Polyoxyethylene sorbitan monooleate), and a denaturant such as ethyl alcohol. Both the aldehyde and acid content of the tissue subjected to Treatment A were less than that of tissue treated with glutaraldehyde alone, with the aldehyde content decreasing by about 25% and the acid content by about 50%. This reduction has been attributed to the further reduction of phospholipids which are sources of acid binding sites as well as hemiacetal formation from alcohol and aldehyde groups.

The left side of FIG. 1 shows the results from testing a total of 10 samples subjected to Treatment B, which is commercially known as the Carpentier-Edwards ThermaFix™ tissue treatment process from Edwards Lifesciences. Treatment B is essentially the same as Treatment A, with the addition of a heat treating step after fixing and prior to sterilizing. Both the aldehyde and acid content of the tissue subjected to Treatment B were less than that of tissue treated glutaraldehyde alone, with the aldehyde content decreasing by about 33% and the acid content by more than 50%. In addition, Treatment B reduces both the aldehyde and acid content relative to Treatment A by between 10-20%.

FIG. 2 is a graph that repeats the results of aldehyde/acid content measurements for the three tissue treatments shown in FIG. 1, and also superimposes measurements of calcium uptake from like tissue samples implanted subcutaneously in rabbits from a separate study. These acid levels are measured in the tissue prior to implant and are likely to increase in vivo. FIG. 2 reveals that the amount of calcium found in the implanted tissues correlates with the levels of aldehydes/acids from the three tissue treatments. That is, as the level of free aldehydes and free acids in the various tissue samples decreases, the amount of calcium absorbed upon implant also decreases. Again, it is understood that a number of factors contribute to calcium uptake, but the availability of certain calcium and phosphate binding sites, among others, is a prime indicator of future calcification. The graph of FIG. 2 therefore suggests that decreasing the levels of aldehydes/acids in the tissue will reduce the propensity for the tissue to calcify.

As mentioned above, it is now understood that oxidation of the aldehyde groups in tissue to carboxylic acid groups produces an increase in calcification. Evidence of this phenomenon is provided in the graph of FIG. 3. Specifically, as explained above, the level of acids in the tissue correlates directly with the propensity to calcify after implant. FIG. 3 indicates the acid levels in various tissue samples. The types of tissue treatments are fresh untreated tissue, glutaraldehyde-fixed tissue, XenoLogiX (XLX), ThermaFix (TFX), ThermaFix tissue treated with glycerol and ethanol only, and the GLX process, which includes treatment with glutaraldehyde, capped with ethanolamine while being reduced with sodium borohydride, and dehydrated with glycerol and ethanol.

FIGS. 4 and 5 are the results of a rabbit intramuscular implant study indicating that the GLX process (described in this invention) significantly reduces calcification over current technology (TFX) and over simple glycerol treatment (GLY-treated). These data also indicate that the GLX process

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reduces variability in calcification. All calcification measurements were measured by atomic absorption spectroscopy and normalized to dry weight of lyophilized tissue.

FIGS. 6 and 7 illustrate that after 80 days of real time shelf life, the GLX treated tissue shows significantly less calcification than TFX or the glycerol treatment alone. The GLX process also reduces variability after 80 days of shelf life. All calcification measurements were measured by atomic absorption spectroscopy and normalized to dry weight of lyophilized tissue.

Based on the foregoing empirical results, the inventors believe that the oxidative damage of dehydrated tissue imparted on bioprosthetic tissue greatly contributes to the propensity for calcification of tissue. In particular, heart valve leaflets not stored in glutaraldehyde are subjected to significant oxidative damage. This deleterious tissue damage process can create new binding sites not previously detected or recognized, as potential attachment sites of calcium and phosphate ions, thereby initiating calcification.

To help prevent this post-implant damage-calcification process, the present invention involves mitigating oxidation by capping the numerous aldehydes that are susceptible to oxidation and increased calcification initiation.

The preferred embodiments include, but are not limited to:

1. The fixed tissue valve or tissue sheet is treated in a solution containing an aldehyde capping agent.
2. Embodiment 1, but where a sterilization step is added during or after the capping process.
3. Embodiments 1 and 2, but where the processing is agitated.
4. Embodiments 1, 2, and 3, but where the capping agent is for the other binding sites such as acids or biological-immune related sites.
5. The aldehyde capping solution may contain an amine (10 mM ethanolamine) and a reducing agent (132 mM sodium borohydride) in 50 mM phosphate buffer at pH 7.4.
6. The tissue or valve is then dehydrated in a glycerol solution
7. The tissue or valve is then sterilized with ethylene oxide

Example 1

Aldehyde capping using ethanolamine and sodium borohydride of glutaraldehyde-fixed tissue. Bioprosthetic tissue was removed from 0.625% glutaraldehyde just after heat treatment step and rinsed in ethanol:saline (20%/80%) for 2 minutes. One liter of capping solution was prepared containing 10 mM ethanolamine (0.06%), and 110 mM sodium borohydride (0.42%) in 50 mM phosphate buffer (pH 7.3-7.8)

The capping solution was placed on an orbital shaker, then tissues (leaflets or valves) were placed in the solution so that they were completely submerged. The ratio of tissue to solution was 3 leaflets per 100 ml or one valve per 100 ml. The container was partly covered but not completely sealed because hydrogen gas liberated by the chemical reaction with water could cause the container to explode. The orbital shaker was operated at between 80-100 rpm for 4 hours at room temperature. The tissue was removed and rinsed in FET solution (formaldehyde, ethanol, tween-80) for three minutes.

Example 2

Glycerol Dehydration Process for Pericardial Valve Bioprosthesis

Pericardial valves were dehydrated by holding each valve with forceps on the sewing ring of the valve and placing the

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valve in a glycerol/ethanol (75%/25%) mixture. Beakers containing the valves were placed on an orbital shaker operating between 50-60 RPM for at least one (1) hour but not more than four (4) hours then immediately treated to remove excess glycerol. This was done by holding them with forceps on the sewing ring of the valve, taking the valve out of the glycerol/ethanol mixture and then placing it on an absorbent towel in a wide mouth jar. After being allowed to dry for at least 5 minutes at room temperature the jar was attached to a lyophilizer and dried for 2 hours. Valves were then transferred to ethylene oxide gas permeable packages and sterilized with ethylene oxide.

Example 3

Calcification Mitigation—Small Animal Model

In order to evaluate the calcification mitigation properties of GLX treated and EO sterilized pericardial tissue, two small animal feasibility studies were conducted. These studies demonstrate that, 1) GLX is superior to TFX in mitigating the occurrence of calcification in tissue, and 2) real time aged GLX tissue is also superior to TFX in mitigating calcification. In both studies, GLX valves demonstrated reduced variability in calcification data when compared to TFX valves. Test methods and results of each are summarized below.

Example 3A

Rabbit Study #1

Calcification Potential of Ethylene Oxide Sterilization on GLX Processed Pericardial Tissue in a 35 Day Rabbit Intramuscular Study. A study utilizing sixty (60) rabbits was conducted to look at the effects on calcification of GLX treated pericardium sterilized using 100% ethylene oxide. The control group was ThermaFix (TFX) processed bovine pericardium and the test group was GLX processed pericardium. Using a sign-rank test, GLX tissue was found to be significantly different ($p=0.0004$) when compared to TFX, and demonstrated a 93% calcification reduction over TFX. GLX data also showed reduced outliers and reduced variability. Box and Whisker plots show an appreciable reduction in variability with the GLX process. Data are presented in FIG. 7, with the y-axis measuring μg calcium/mg dry weight tissue.

Example 3B

Rabbit Study #2

Effects of a Short Term Shelf Life on Calcification of GLX Processed Pericardial Tissue in a 35 Day Rabbit Intramuscular Study. A second study utilizing sixty (60) additional rabbits was conducted to look at the effects on calcification of short term shelf life of GLX processed pericardium. The control group was ThermaFix (TFX) processed bovine pericardium and the test group was GLX processed pericardium.

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The GLX tissue samples were packaged in Tyvek pouches and sterilized via 100% ethylene oxide. GLX samples were stored in a controlled steady state chamber at 25° C. and 60% humidity for a period of 83 days. The TFX samples had not been aged. In this study the GLX processed tissue demonstrated significantly reduced levels of calcification, 73% compared ($p=0.009$) to TFX as well as reduced outliers and reduced variability in the data. Data are presented in FIG. 8, with the y-axis measuring μg calcium/mg dry weight tissue.

While the invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description and not of limitation. Therefore, changes may be made within the appended claims without departing from the true scope of the invention.

What is claimed is:

1. A bioprosthetic tissue comprising:

an at least partially cross-linked biological tissue comprising one or more functional groups that have been reacted with an ethanolamine, a hydroxylysine, a taurine, a dextran sulfate, a chondroitin sulfate, a polyvinyl alcohol, a 3-deoxyglucosone, a hydrazine, an adipic hydrazide, and a heparin, wherein the functional groups are selected from the group consisting of an aldehyde and a carboxylic acid.

2. The bioprosthetic tissue of claim 1, wherein the biological tissue is selected from the group consisting of: bovine pericardium, porcine tissue, blood vessels, skin, dura matter, pericardium, small intestinal submucosa, tissue heart valves, ligaments, and tendons.

3. The bioprosthetic tissue of claim 1, wherein the biological tissue is at least partially cross-linked with glutaraldehyde or other aldehyde-containing agents.

4. The bioprosthetic tissue of claim 1, wherein the at least partially cross-linked biological tissue is exposed to a reducing agent.

5. The bioprosthetic tissue of claim 4, wherein the reducing agent is a sodium borohydride or a sodium cyanoborohydride.

6. The bioprosthetic tissue of claim 1, wherein the at least partially cross-linked biological tissue comprises glycerol.

7. The bioprosthetic heart valve of claim 6, wherein the at least partially cross-linked biological tissue is sterilized by ethylene oxide, gamma irradiation or electron beam irradiation.

8. The bioprosthetic tissue of claim 1, wherein the at least partially cross-linked biological tissue is at least partially dehydrated.

9. The bioprosthetic heart valve of claim 8, wherein the at least partially cross-linked biological tissue is sterilized by ethylene oxide, gamma irradiation or electron beam irradiation.

10. A packaged bioprosthetic heart valve comprising:

a bioprosthetic heart valve comprising the bioprosthetic tissue of claim 1; and

a sterile packaging;

wherein the bioprosthetic heart valve is stored in the sterile packaging without a liquid preservative solution.

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